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RICE UNIVERSITY

HOUSTON, TEXAS

ROCKET AND SATELLITE OBSERVATIONS OF ENERGETIC PARTICLES DURING P.C.A. EVENTS*

by

Brian J. O'Brien

Department of Space Science
Rice University
Houston, Texas

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Brian J. O'Brien

Rice University
Houston, Texas

Abstract. A critical review is given of direct measurements of particles that cause PCA events and are associated with them. Such measurements have been made with balloons, rockets, satellites and space probes, and on occasions several of these vehicles have been used in studies of the same event. Particular attention is given to the variation in space and time of the particle intensities, charge and energy spectra, pitch-angle distributions for several selected events rather than to a comprehensive catalog of all observed events. An attempt is then made to assess the significance of these measured parameters as regards to both their causes and their effects. Some experiments that may aid such assessments are described.

INTRODUCTION

Polar Cap Absorption (PCA) events are caused when the polar cap ionosphere is bombarded by solar cosmic rays. Enhanced ionization is produced down to altitudes of some 50 km, and the resultant enhanced absorption of cosmic radio-signals is the effect that historically gave rise to the title "PCA" event. Early studies were enforced to concentrate on the atmospheric effects per se. But rockets and satellites have given the opportunity to measure the bombarding particles themselves with resultant potential studies of the phenomenology of these particle fluxes (their origin, propagation, etc.) on the one hand and of the ionospheric effects they produce on the other hand. In this note we concentrate on the particle fluxes themselves, and restrict discussion to measurements made over the polar caps, where the geomagnetic field has gained control of these particles. Other papers in the Symposium will deal with these fluxes directly observed in interplanetary space (McCracken, K., "Interplanetary Propagation and Storage of Energetic Solar Particles") and by balloons in the earth's atmosphere (Brown, R., "Balloon Observations during PCA Events").

HISTORICAL SUMMARY OF ROCKET AND SATELLITE SOLAR COSMIC-RAY MEASUREMENTS

The first satellite-borne detection of solar cosmic rays was apparently with Explorer IV [Rothwell, P. and C. McIlwain, 1959]. The detectors in this case were simply omnidirectional shielded geiger tubes.

The longest-duration satellite monitoring of solar cosmic rays was performed - again with omnidirectional geiger tubes - with Explorer VII from October 13, 1959 through February 1961 [W. C. Lin, 1961]. It is one of those exquisite ironies of space research that Explorer VII was equipped with a "killer timer" to cut off telemetry (and thus avoid RF interference) after one year, i.e. on October 13, 1960. The "killer timer" failed to operate, and one month later the satellite measured the most intense solar-cosmic-ray event yet detected in space, viz the November 12, 1960 event. From November 12 to November 16, 1960 the total integrated flux of protons with energy $E > 40$ Mev was 2×10^9 particles cm^{-2}. J. R. Winckler [1963] estimates the total radiation dosage from such a flux - if it were isotropic - would be some 700 rad.

More sophisticated instruments in rockets and satellites gradually provided data on the following parameters of solar cosmic rays observed over the polar cap:

(1) time variation

(2) spatial dependence

(3) energy spectra

(4) composition

and (5) pitch-angle distribution, etc.

It is these aspects that this paper will treat in detail. We neglect the extremely important satellite studies made outside the magnetosphere [cf Bryant, et al., Feb. 1965 and Solar Proton Manual].

TIME VARIATIONS

Time variations of a solar cosmic ray event have as their zero in time the eruption of the parent solar flare as measured optically or from the x-ray burst [Anderson, K. A., 1964]. Near-relativistic protons may reach the earth within some minutes to hours. Lower-energy particles may take several days to reach the earth.

A quite remarkable ordering of the disparate arrival times for various energies was achieved by Bryant et al. [Feb. 1965] in considering a diffusion process of propagation from the sun to the earth. The intensities of protons of several energies was plotted - not against time - but against time multiplied by the individual velocity, thus equivalent to a distance travelled. The effect is illustrated in Figures 1 and 2.

The relevance here to PCA events is that, over the polar cap, both the intensity of particles with a given energy and the energy spectrum may change greatly with time during an event, as well as from event to event [see also Pieper, et al., 1962]. Consequently, ground-based observers who may have many hours of continuous PCA data must treat an occasional short-duration sample by a rocket or satellite with care since the magnitude of the PCA is of course, dependent on both particle intensity and energy [cf Maehlum and O'Brien, 1962].

A very interesting short-time (~ one hour) periodic modulation of solar cosmic rays has been observed directly, with all energies varying in phase [Bryant, et al., Feb. 1965]. No comparable ground-based observations are known to us.

Gregory's observations [1962] of turbulent scattering of 2.3 Mc/s radio waves were used by him to imply that there was a common or persistent flux of protons of order 1 Mev with fluxes of order 100 $cm^{-2} sec^{-1}$. Those observations were made in 1959-1961 when solar cosmic ray activity was reasonably large. It seems possible - but by no means certain - that these data might be explained as being caused by the continued acceleration of solar protons in the Mev region. For example, Bryant et al. [March 1965] found persistent fluxes of such protons with the satellite Explorer XIV in 1962. These fluxes were associated with at least seven consecutive solar rotations over a six-month period, and may be linked with M-region disturbances. Bryant, et al. [March 1965] found fluxes of protons of a few Mev of some 100 particles $cm^{-2}sec^{-1}$ so it seems not at all unreasonable to equate these with the phenomena reported by Gregory [1962]. A very important measurement is therefore monitoring by a polar-orbiting satellite of the fluxes of such polar-cap protons with energies of say 100 kev to 10 Mev. The relevant detectors must be able to measure fluxes as small as 1 particle $cm^{-2}sec^{-1}$ or less in order to be really effective.

SPATIAL DEPENDENCE

Such early studies as the joint and simultaneous observations by Van Allen and Lin [1960] with the near-earth orbiter Explorer VII and by Winckler, et al. [1960] with the Pioneer V spacecraft five million kilometers away showed the vast extent of solar cosmic ray beams. But in this note here again we are concerned only with the narrow context of the spatial dependence over the polar cap.

The spatial dependence may be treated as

(a) a latitude effect in one hemisphere

(b) a longitude or local-time effect

and (c) a conjugate effect.

Such observations as those of Lin [1961] with the omni-directional detectors on Explorer VII show the first or latitude effect very clearly. Suppose one can observe protons of, say, 40 Mev. At low magnetic latitudes they are excluded by the geomagnetic field. As the satellite travels to higher latitudes it may reach a magnetic latitude (λ) or an L-shell [cf McIlwain, 1961] which is termed the cut-off latitude above which it can travel on allowed trajectories to near the earth, bombarding the atmosphere to cause PCA's, etc. It is the existence of this cut-off latitude when combined with the preponderance of lower-energy solar cosmic rays, that leads of course, to the confinement to the "polar cap".

It has been shown that the L-shell parameter is a useful ordering parameter for satellite studies of solar cosmic rays [see Akasofu, S.-I., et al., 1963 and Pieper, et al., 1962]. The "cut-off" value of L decreases during the main phase of a geomagnetic storm. In other words, the well-known effect is that the PCA event extends to lower latitudes. Quantitative treatment of the significance of these shifts and of the actual cut-off values are beyond the scope here, but see Akasofu, S. I., et al., [1963].

There is special interest in the "knee" or vicinity of the cut-off for several reasons. Just below the knee the relevant solar cosmic ray is a "Stoermer-like" excluded particle. In the middle of the knee it is still a Stoermer-like particle as particular trajectories become allowed, and the cone of allowed trajectory lies initially in the east. It then gradually (with increase in λ) opens up until it fills the whole sky, at which latitude one is above the knee and in the true polar cap. But an interesting point is that solar cosmic rays with energies of some Mev in the polar cap are actually "Alfven-like" particles. (The radius of gyration of a 1 Mev proton above the polar cap is about 2 km, and that of a 10 Mev proton is about 8 km). Consequently, in the polar cap, one can define a "loss-cone" for solar cosmic rays just as one can for precipitated electrons [see O'Brien, 1964] and it is only the particles in the loss cone that cause the PCA event. The others "mirror" and then travel back up along the geomagnetic field lines. If the field lines have not been perturbed, the particles presumably are "lost" along trajectories similar to those that they followed in entering the polar cap.

Indeed, even though in the polar cap these particles are Alfven particles, yet their intensity does not monotonically increase with time as one might expect if they were being trapped durably (i.e. to bounce to and fro from hemisphere to hemisphere). The implication is that polar cap magnetic field lines cannot retain trapped particles. In 1961, O'Brien [1963] found that this held true for Van Allen radiation since there exists a "high-latitude boundary" of trapping.

The question then arises as to whether the high-latitude boundary of trapping of Van Allen particles is coincident with the low-latitude boundary of solar cosmic rays for suitably-low energies. I believe that this is experimentally not resolved at the present time. It is a difficlut point to resolve since there are violent acceleration processes that lead to precipitation of auroral particles at much the same location [O'Brien, 1964].

Michel and Dessler [1965] pursued this problem theoretically. They considered the geomagnetic field to have a very long tail, and that on the boundaries of this tail were the field lines from the auroral zones. The field lines from the poles then, were buried inside this tail. Consequently, they argue, low-energy solar cosmic rays diffusing into the tail would first bombard the polar cap in a halo (effectively at the auroral zone) and then later the halo would broaden to higher latitudes, finally to envelope the pole. This process would take a few hours on their model, and it was suggested as applicable to proton energies of some few Mev.

While there are no satellite observations of such an effect, it is not clear that there are any satellite measurements to prove it invalid. The critical joint requirements of timing of the satellite pass at the PCA onset, with measurements of very low-energy particles, to my knowledge have not yet both been met with the precision necessary to refute the model or a variation of it. An appropriately instrumented satellite should measure Van Allen radiation, auroras and solar cosmic rays simultaneously to resolve this problem.

There are some observational problems as a consequence of this transition from a Stoermer-like particle to an Alfven-like particle at the knee. Briefly, there will be an azimuthal asymmetry in flux. H. R. Anderson [private communication] has calculated that for a dipole field the cut-off latitudes of protons of 10 Mev energy is about two cyclotron radii or some 15 km lower for particles from the east than it is for those from the west. If one has a directional detector pointed perpendicular to $\vec{B}$ on a magnetically-oriented satellite this effect must be taken into account. There is of course, another east-west asymmetry introduced when the radius of gyration is larger than the atmospheric scale height, but for PCA particles this is a negligible effect at satellite altitudes.

Related again to the cut-off latitude or "edge" of the polar cap is the overall magnetospheric configuration. O'Brien [1963] found that the high-latitude boundary of Van Allen radiation was some 6° higher in the day than in the night. Reid and Sauer [1966] suggest that a similar effect might exist, with PCA's, thereby explaining a "midday recovery". Indeed, if our speculation above is valid, such an effect must occur. The same polar-orbiting satellite referenced above could again solve this matter.

A more complex but still related problem is whether PCA edges are magnetically conjugate. To resolve this with satellites without significant time delays between the measurements in the two hemispheres requires the use of two satellites in crossed orbits, such as will be followed in 1967 by the Rice University/ NASA Owl Satellites (Figure 4).

ENERGY SPECTRA

The energy spectra of solar cosmic rays vary both in time and from event to event, as already noted. In the vicinity of the "knee" or low-latitude edge of the polar cap, the energy spectrum of course will vary as particles of below a given rigidity are excluded. Such effects may lead to apparent temporal variations in the particle flux as the knee advances and retreats from the observer. But in general here we treat the true polar cap fluxes assumed to be unperturbed by the geomagnetic field.

Pieper, et al. [1962] show how the energy spectra can vary greatly from event to event. For example, they compare the ratio of proton intensities for energy (E_p) of 1 to 15 Mev and energy $E_p \geq 40$ Mev. The measurements were made with the satellite Injun 1 at 1000-km altitude over the polar cap, and the fluxes were measured as several magnetic storms waxed and waned. In the event of July 13, 1961, for example, the above ratio during the main phase was about 3000 to 1. However, in the next storm only five days later the ratio was about unity. In another storm a few days later the ratio approached 100.

These measurements were made inside the polar cap and they may not be indicative of the solar cosmic ray fluxes then prevailing in interplanetary space. Certainly they cannot be ordered with the diffusion approach used so successfully by Bryant et al. [Feb. 1965]. What is necessary is a low-altitude satellite study with comparable energy resolution, as as to resolve the three determinant parameters in the energy spectra, viz

(a) variations in the solar outburst (source)

(b) variations in conditions in interplanetary space,

and (c) variations in geomagnetic conditions, eg. location of the knee, conditions in the geomagnetic tail, etc.

Such a study might be carried out with rocket probes [cf. Davis, et al, 1961] but only if the launch site is deep in the polar cap beyond the effect of time changes in the latitude of the "knee".

COMPOSITION

Although the ionospheric properties in a PCA event are somewhat dependent on the composition of the solar cosmic rays [cf. Brown, 1964], deduction of their charge composition from other than direct measurements is impracticable.

Biswas and Fichtel [1965] and Biswas, Fichtel and Guss [1966] have reviewed the balloon, rocket and satellite measurements of the relative nuclear abundances. We may mention here that although there are relativistic electrons encountered over the polar cap [cf. Meyer and Vogt, 1962] their effects in PCA events are negligable.

The solar cosmic rays have a charge composition or relative nuclear abundances that seem consistent with the relative composition of the sun. Indeed, it is sometimes suggested that the measured ratio of protons to alpha particles is a more accurate measurement of the relative abundances of solar hydrogen and helium than can be provided by optical means. But this p/α ratio varies greatly with particle energy, so such interpretations must be made with care, since they are dependent upon interplanetary conditions, the local cut-off rigidity, etc. For example, Figure 5 shows the variation of the p/α ratio between about 10 to 1 and 500:1 as a function of kinetic energy/nucleon.

The relation between nuclei other than protons appears constant in time. There have been measurements of heavy nuclei in four solar cosmic ray events. The "helium to medium ratio could be exactly the same for the whole duration of every event, with the best estimate of this ratio being about 62 ± 7" [Biswas, Fichtel and Guss, 1966].

However, the proton to helium ratio, if compared in the same rigidity ranges, varies by a factor of about 50 from event to event.

In general then, we may conclude that the charge composition of solar cosmic rays, observable only with balloons, rockets or satellites may yield useful data on both the solar composition and on propagation of solar cosmic rays through interplanetary space. Because multiply-charged particles have a charge-to-mass ratio one half that of protons, their rigidity differs from that of a proton with the same velocity, although their rigidity is about the same at a given velocity for charge $Z \geq 2$. Since the helium to medium ratio is the same from event to event, one might deduce that the p/α changes arose because of their rigidity differences. But the ratio changes, even at the same rigidity, are so large that a simple rigidity-dependent propagation from the earth to the sun must be excluded [see Biswas and Fichtel, 1965, for further discussion].

ANGULAR DISTRIBUTION

We have already treated briefly the reasons why the angular distribution of solar cosmic rays above the polar cap need not be isotropic over the upper hemisphere. Some observations of anisotropies near the knee were made with the satellite Injun 1 during the July 13, 1961 event, but the data derived from the slowly-tumbling satellite were not adequate to do other than indicate the existence of some anisotropy [O'Brien, unpublished].

The relevance of this point with regard to PCA events deep in the polar cap is simply the quantitative interrelation of satellite observations of solar cosmic ray fluxes with ground-based observations of ionospheric effects. Only solar cosmic rays in the loss cone will hit the atmosphere. To relate the two types of measurements one can either

(a) track the directional flux in the loss cone down into the atmosphere and multiply by 2π sterads, or

(b) take the omnidirectional flux at the satellite, convert it to a directional flux over the entire sphere less the size of the loss cone (since for protons few particles occupy the loss cone moving upwards from the earth), and then follow step (a).

One can carry out such calculations simply by invoking Liouville's theorum and the first (magnetic moment) invariant. The directional flux along an allowed trajectory is a constant. If the satellite measurement of particles $cm^{-2}sec^{-1}$ was made at an altitude of say 1000 km, the loss cone is approximately 60^o wide in half-angle. Consequently only some 3π sterads are filled with the radiation. But in the ionosphere only some 2π sterads will be so filled (i.e. the upper hemisphere). Consequently, if one measures the omnidirectional flux J_o particles $cm^{-2}sec^{-1}$ at the satellite the flux of particles bombarding the atmosphere will be only $2/3\ J_o$. If one measures the directional flux j particles $cm^{-2}sec^{-1}sterad^{-1}$ in the loss cone at the satellite altitude, then the flux bombarding the atmosphere will be j particles $cm^{-2}sec^{-1}sterad^{-1}$ or simply $(2\pi\ j)$ particles $cm^{-2}sec^{-1}$, whereas the flux bombarding the satellite detector would be about (3π j) particles $cm^{-2}sec^{-1}$. The correction is clearly altitude dependent because of the changing size of the loss cone. It is also energy dependent because charge exchange processes can severely modify ("neutralize") fluxes of protons of say 100 kev up to altitudes of several hundred kilometers.

CONCLUSIONS

We have restricted discussion to the narrow confines of space-borne measurements directly pertinent to PCA events and their interpretation. Progress in this subject will be materially increased with further experimental satellite-borne measurements capable of resolving, for example, whether the auroral zone, the PCA low-latitude edge and the Van Allen high-latitude boundary are coincident. Other critical measurements are those to resolve conjugacy and local-time effects, pitch-angle effects and so on. Coordinated rocket firings under an orbiting satellite can be used to obtain vertical profiles of particle fluxes, ionization and absorption with which to relate the satellite measurements and PCA data.

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FIGURE CAPTIONS

Fig. 1: Time variations of fluxes of protons of various energies. [After Bryant, et al., Feb. 1965].

Fig. 2: Coherence of data when Fig. 1 is replotted again distance travelled. [After Bryant, et al., Feb. 1965].

Fig. 3: Short-time fluctuations of primary solar cosmic rays [After Bryant, et al., Feb. 1965]. The effects are coherent at several energies [see also Anderson, 1964].

Fig. 4: The use of two simultaneously-operative Owl satellites with near-coincident antiparallel lines of nodes. Computer calculations for the real geomagnetic field indicate at least one period each week when the satellites will execute magnetically-conjugate passes with time delays of less than 1 minute and dispersion in magnetic longitude of less than 2°.

Fig. 5 Variation of the proton/alpha ratio as a function of rigidity [After Biswas, Fichtel and Guss, 1966].

REFERENCES

Akasofu, S-I., W. C. Lin and J. A. Van Allen, The Anamalous Entry of Low-Rigidity Solar Cosmic Rays into the Geomagnetic Field, J. Geophys. Res., 68, 5327-5338, 1963.

Anderson, H. R., Private Communication

Anderson, Kinsey A., Energetic Solar Particles Chapter 16, Space Physics, edited by Donald P. LeGalley and Alan Rosen, John Wiley & Sons, New York, New York, 1964.

Biswas, S., C. E. Fichtel and D. E. Guss, Solar Cosmic Ray Multiply Charged Nuclei and the July 18, 1961 Solar Event, NASA Publication X-611-66-137, Goddard Space Flight Center, Greenbelt, Md., April 1966.

Biswas, S., and C. E. Fichtel, Composition of Solar Cosmic Rays, Space Science Reviews, 4, 709-736, 1965.

Brown, R. R., On the Influence of Composition and Spectra of Solar Cosmic Rays on the Intensity Ratio I(λ5577)I(λ3914) in Polar-Glow Aurora, Planet. Space Sci., 12, 665-674, 1964.

Bryant, D. A., T. L. Cline, U. D. Desai and B. McDonald, The Continual Acceleration of Solar Protons in the MeV Region, NASA Publication X-611-65-107, Goddard Space Flight Center, Greenbelt, Maryland, March 1965.

Bryant, D. A., T. L. Cline, U. D. Desai and F. B. McDonald, Studies of Solar Protons with Explorers XII and XIV, Astrophys. J. 141, No. 2, February 15, 1965.

Davis, L. R., C. E. Fichtel, D. E. Guss and K. W. Ogilvie, Rocket Observations of Solar Protons on September 3, 1960, Phys. Rev. Lett. 6, 492, 1960.

Gregory, J. B., Residual Ionization in the Polar Lower Ionosphere, J. Geophys. Res., 67, 3829-3841, 1962.

Lin, W. C., State University of Iowa Research Report, 60-16, 1961.

Maehlum, B. and B. J. O'Brien, Solar Cosmic Rays of July 1961 and Their Ionospheric Effects, J. Geophys. Res., 67, 3269, 1962.

McIlwain, C. E., Coordinates for Mapping the Distribution of Magnetically Trapped Particles, J. Geophys. Res., 66, 3681-3691, 1961.

Meyer, P. and R. Vogt, Phys. Rev. Letters, 8, 387, 1962.

Michel, F. C. and A. J. Dessler, Physical Significance of Inhomogeneities in Polar Cap Absorption Events, J. Geophys. Res. 70, 4305-4311, 1965.

O'Brien, B. J., A Large Diurnal Variation of the Geomagnetically-Trapped Radiation, J. Geophys. Res., 68, 989-996, 1963.

O'Brien, B. J., High-Latitude Geophysical Studies with Satellite Injun III, Part 3, Precipitation of Electrons into the Atmosphere, J. Geophys. Res., 69, 13-44, 1964.

Ogilvie, K. W., D. A. Bryant and L. R. Davis, Rocket Observations of Solar Protons during the November 1960 Event's, J. Geophys. Res., 67, 929-937, 1962.

Pieper, G. F., A. J. Zmuda, C. D. Bostrom, and B. J. O'Brien, Solar Protons and Magnetic Storms in July 1961, J. Geophys. Res., 67, 4959-4981, 1962.

Reid, G. C. and H. H. Sauer, The Influence of the Geomagnetic Tail on Low-Energy Cosmic-Ray Cutoffs, Publication of Institute for Telecommunication Sciences and Aeronomy, Boulder, Colorado, 1966.

Rothwell, P. and C. McIlwain, Satellite Observations of Solar Cosmic Rays, Nature, 184, 139-140, 1959.

Solar Proton Manuel, NASA X-611-62-122 edited by Frank B. McDonald, Goddard Space Flight Center, Greenbelt, Md., revised January 25, 1963.

Van Allen, J. A., W. C. Lin, and H. Leinbach, On the Relationship between Absolute Solar Cosmic Ray Intensity and Riometer Absorption, J. Geophys. Res., 69, 4481-4491, 1964.

Van Allen, J. A., and W. C. Lin, Outer Radiation Belt and Solar Proton Observations with Explorer VII during March-April 1960, J. Geophys. Res., 65, 2998-3003, 1960.

Winckler, John R., R. L. Arnoldy, and R. A. Hoffman, Solar Cosmic Rays and Soft Radiation Observed at 5,000,000 kilometers from Earth, J. Geophys. Res., 65, 3004-3007, 1960.

Winckler, John R., The Production and Propagation of Energetic Particles from the Sun, Chapter 11, Space Science, edited by Donald P. LeGalley, John Wiley and Sons, New York, New York, 1963.

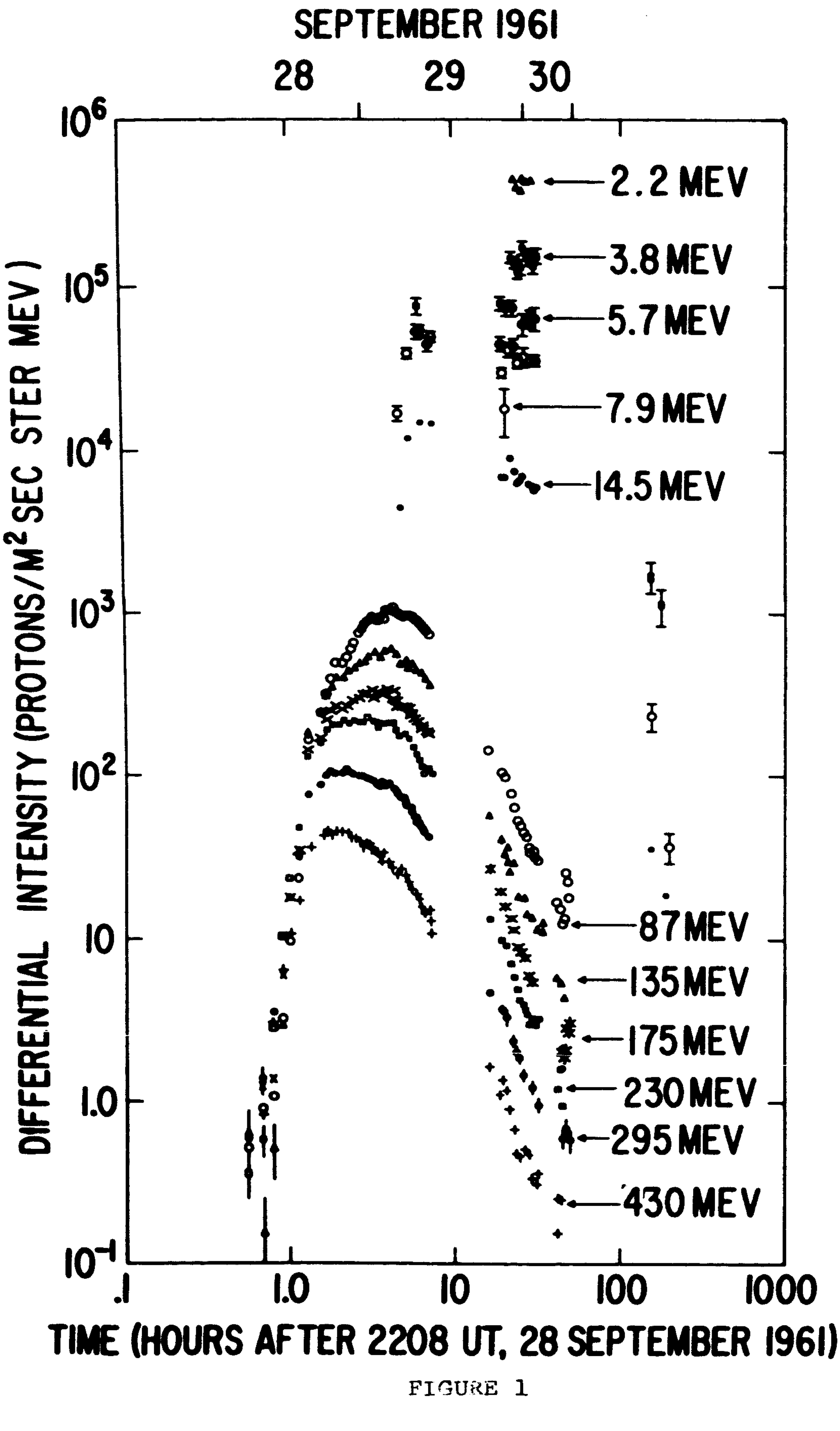
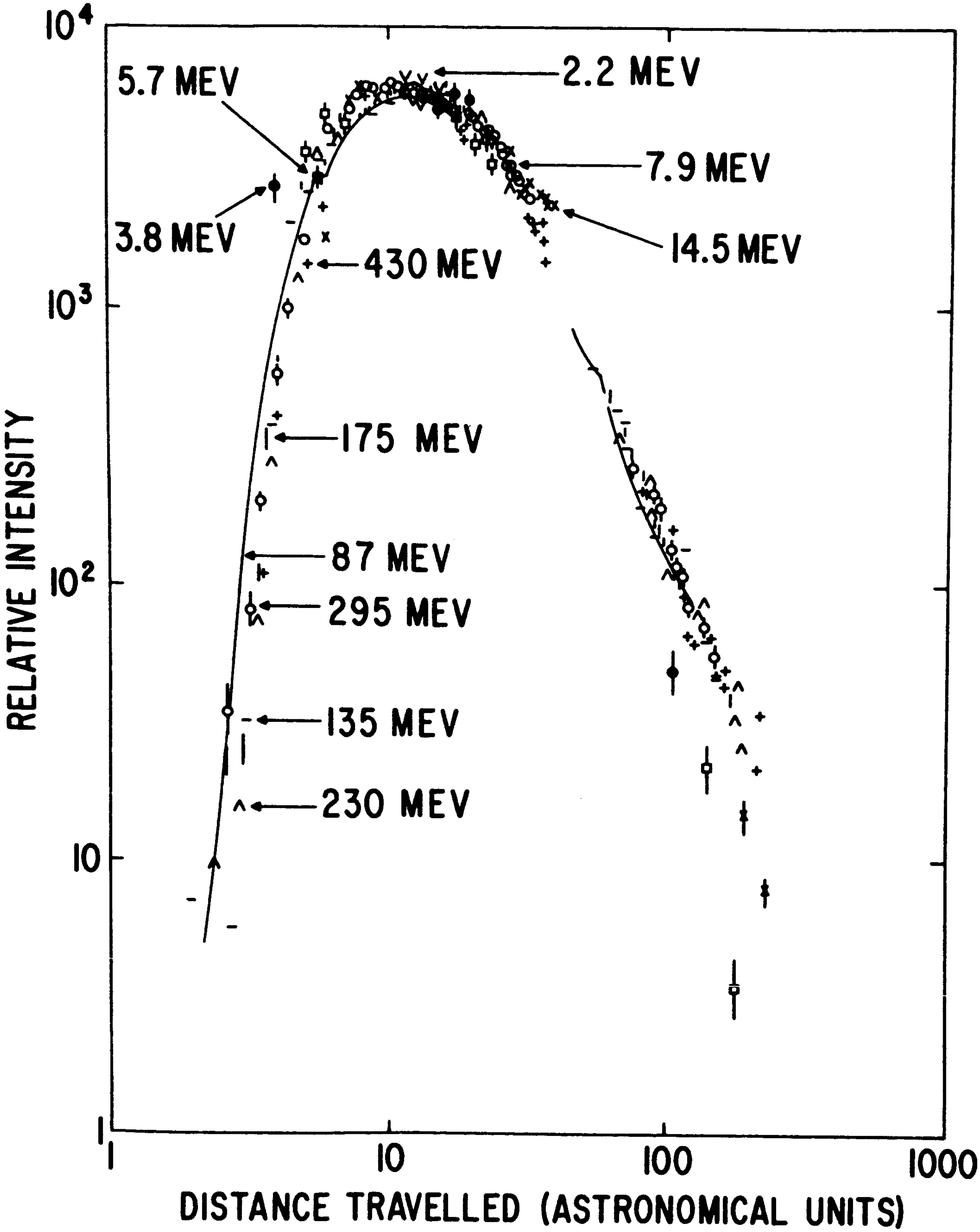

SEPTEMBER 1961
28
29
30
10^6
10^5
10^4
10^3
10^2
10
1.0
10^{-1}
DIFFERENTIAL INTENSITY (PROTONS/M^2 SEC STER MEV)
2.2 MEV
3.8 MEV
5.7 MEV
7.9 MEV
14.5 MEV
87 MEV
135 MEV
175 MEV
230 MEV
295 MEV
430 MEV
.1
1.0
10
100
1000
TIME (HOURS AFTER 2208 UT, 28 SEPTEMBER 1961)

FIGURE 1



10⁴
10³
10²
10
1
5.7 MEV
2.2 MEV
7.9 MEV
3.8 MEV
14.5 MEV
430 MEV
175 MEV
87 MEV
295 MEV
135 MEV
230 MEV
RELATIVE INTENSITY
1
10
100
1000
DISTANCE TRAVELLED (ASTRONOMICAL UNITS)

FIGURE 2

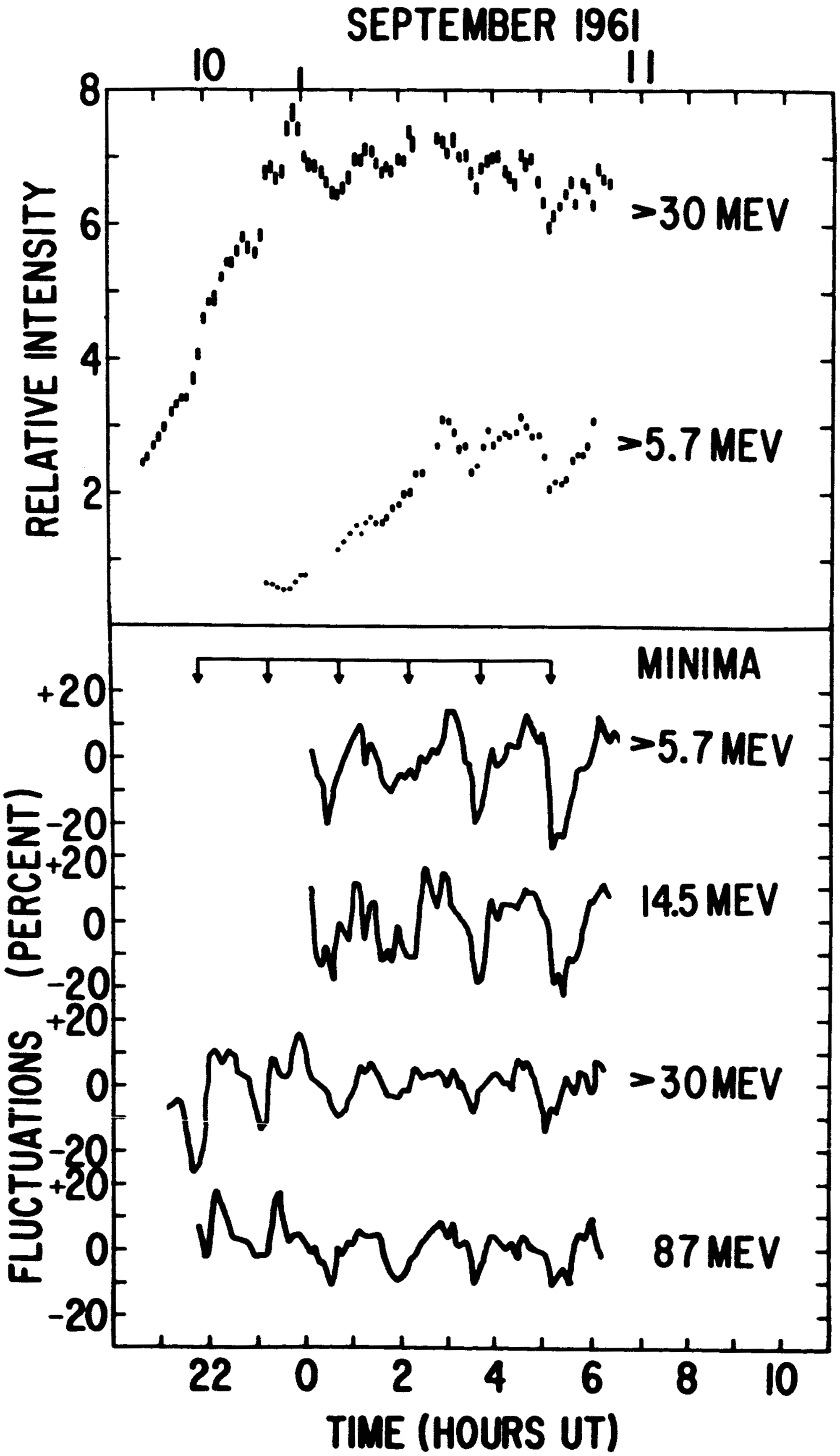
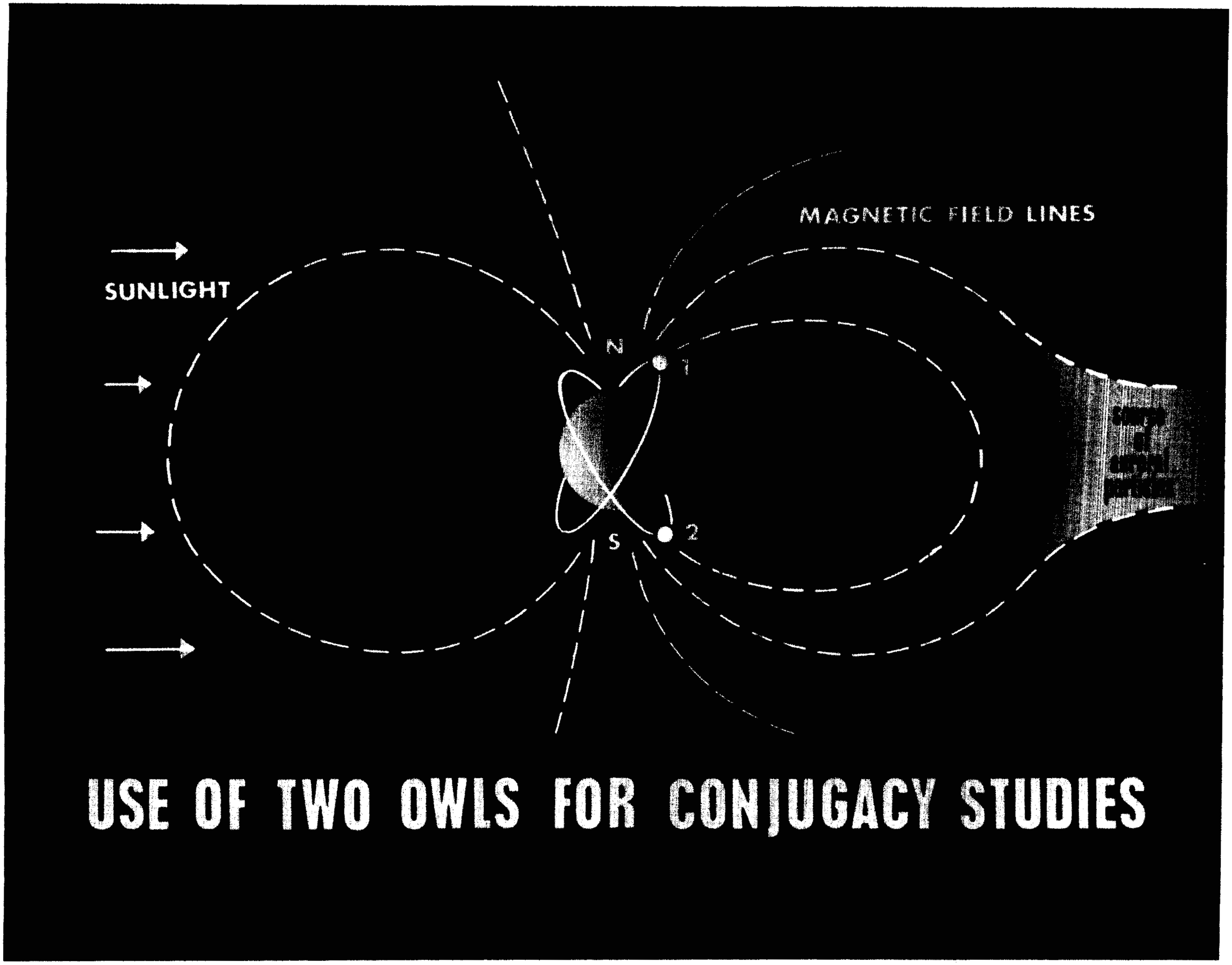
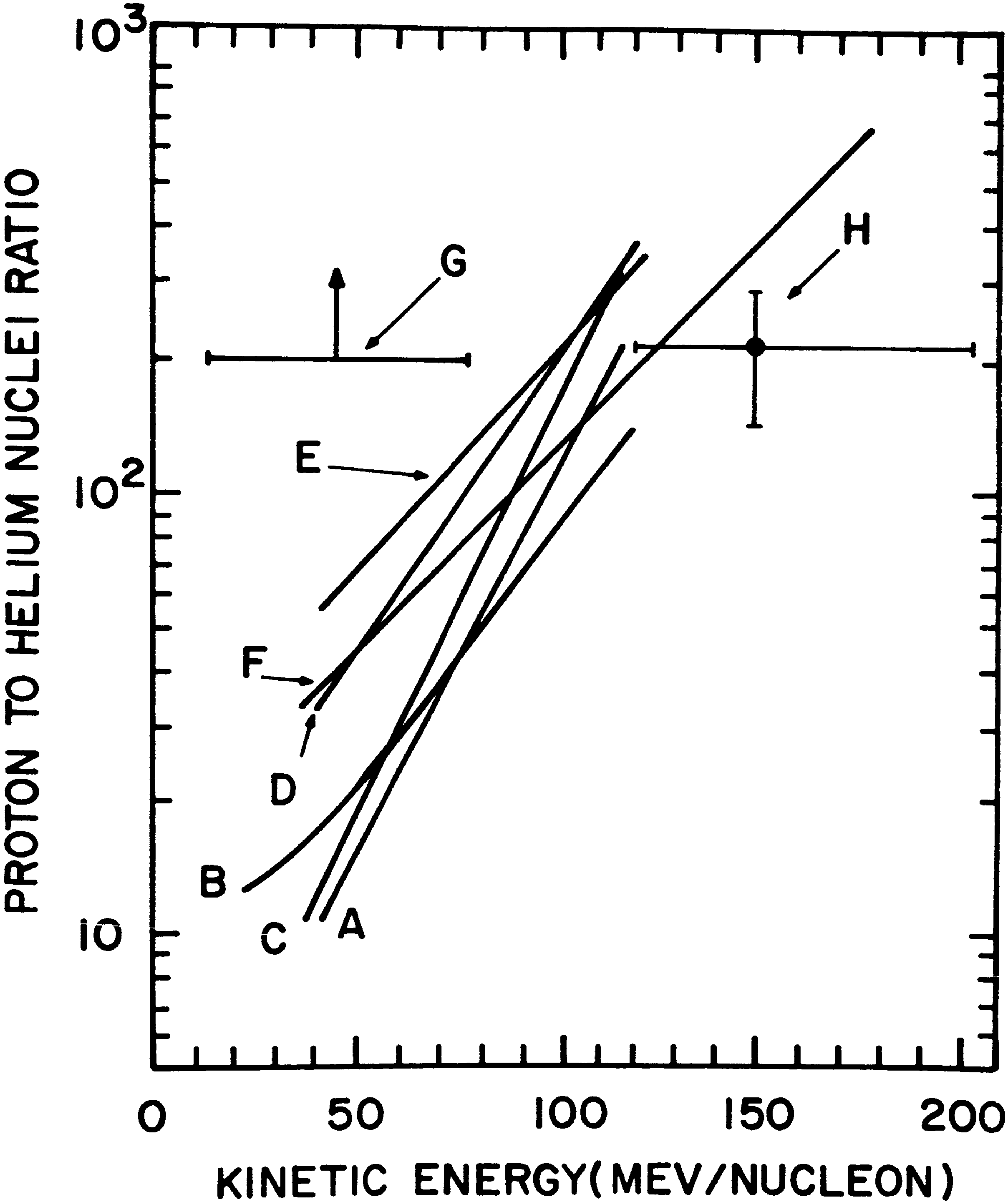

SEPTEMBER 1961
10
11
RELATIVE INTENSITY
8
6
4
2
>30 MEV
>5.7 MEV
MINIMA
FLUCTUATIONS (PERCENT)
+20
0
-20
>5.7 MEV
14.5 MEV
>30 MEV
87 MEV
22
0
2
4
6
8
10
TIME (HOURS UT)

FIGURE 3


MAGNETIC FIELD LINES
SUNLIGHT
N
S
1
2
USE OF TWO OWLS FOR CONJUGACY STUDIES



PROTON TO HELIUM NUCLEI RATIO
10^3
10^2
10
0
50
100
150
200
KINETIC ENERGY(MEV/NUCLEON)
A
B
C
D
E
F
G
H

FIGURE 5